Investigation of the Interaction of Elastic Waves with Buried Mines

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Grant Number: N00014-99-1-0995
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Land mine detection using seismic waves

LONG-TERM GOALS

1. Understand the interaction between elastic/high-frequency seismic waves and buried land mines.

2. Establish a link between experimental models, numerical models, and field measurements of high-frequency seismic waves.

3. Define the component configuration of a fieldable seismic mine detection system.

OBJECTIVES

1. Develop a three-dimensional (3-D) finite-difference time-domain (FDTD) model for seismic wave propagation and scattering.

2. Refine the 3-D FDTD model so that it runs efficiently on a massively parallel computer.

3. Develop structurally detailed 3-D FDTD models for a representative set of land mines.

4. Incorporate the non-linear nature of the soil into the 3-D FDTD model.

5. Characterize the properties of damp compacted sand using an experimental model and a field test site.

6. Use the 3-D FDTD model to study the interactions of the seismic waves and land mines as a function of land mine type, burial depth, and the type and frequency of the seismic waves.

7. Use the 3-D FDTD model to refine possible configurations of a fieldable seismic mine detection system.

APPROACH

This work is a combined theoretical and experimental investigation of elastic wave propagation in the earth and the interaction of these waves with buried objects such as land mines. A theoretical model for elastic waves propagating in the earth (that was developed previously) is significantly extended. Since the physical properties of the soil and the mines (that are needed for the model) are not well understood at the frequencies of interest, they are measured and studied as part of the investigation. The theoretical model is validated by comparison with experimental measurements. This research is a collaborative effort between Georgia Tech and the Naval Postgraduate School (NPS), with the theoretical modeling being performed at Georgia Tech and the experimental measurements being performed at both locations.

The results from the previous developed theoretical model are only in fair agreement with the experimental findings. This is due to several approximations used to simplify the model. The most significant of these approximations is that the model is two-dimensional whereas the experiments are three-dimensional. In addition, the soil in the model (damp, compacted sand) is considered to be linear, homogeneous, and lossless. However, it is clear from the experimental results that the sand is non-linear, inhomogeneous, and lossy. The mines are considered to be a solid elastic block with an air chamber on top. Actual land mines are complicated mechanical structures with a flexible case, a trigger assembly, air pockets, etc. The complex structure gives rise to structural resonances, non-linear interactions, and other phenomenology. The previously developed model for the mines is not adequate to accurately predict these interactions accurately. In this work, the model is extended to three dimensions to include the non-linear, inhomogeneous, and lossy nature of the sand, and to include the complex mechanical structure of the mine. The three-dimensional model is much more computationally intensive than the two-dimensional model, and, therefore, it is impractical to run it on a serial computer. Consequently, the model is developed to run on a massively parallel computer.

The physical properties of both the mine and the sand must be understood before an accurate model can be constructed. The properties of the sand are clearly dispersive, non-linear, and lossy. The dispersion is mostly due to the increase of the shear wave velocity with increasing depth and the non-linearities are due to the shearing of the sand. These properties have not been studied previously for the frequency ranges of interest for this work. Almost all of the work on elastic wave propagation is for lower frequencies and greater depths than those used here. Geophysicists generally view these surface waves as noise and try to eliminate them from their measurements. These properties are measured both by Georgia Tech and the NPS. The properties of the sand in the experimental facility are studied at Georgia Tech and the properties of sand on the beach are studied at the NPS.

The three-dimensional model is used to investigate elastic wave propagation in the sand. The interactions of the waves with mines are investigated as a function of the mine type, the burial depth, and the type and frequency of the elastic waves. The strength of the reflected waves, the resonances, the non-linear interactions are determined. The source of the elastic waves is also investigated. The current source seems to be limited by the non-linear nature of the sand. It is hoped that this investigation will facilitate the design of a better source. The model is used to investigate other configurations for the mine detection system.

The following is a list of key individuals participating in this work and a brief description of the roles they play:

Waymond R. Scott, Jr., Ph.D.: Project Director and Principal Investigator

Peter H. Rogers, Ph.D.: Co-Principal Investigator

James, S. Martin, MSME: Co-Principal Investigator, experimental hardware design

Gregg L. Larson, Ph.D.: experimental measurements and analysis

George S. McCall II, MSME: assistant project director

Graduate Students: Blace Albert, Fabien Codron, Kong-Wook Kim, Seung-Ho Lee, Andrew Overway, Christoph Schroeder, Andrew Slack.

Tom Muir, Ph.D.: Chair, Mine Warfare, Naval Postgraduate School

WORK COMPLETED

Three-dimensional (3-D) finite-difference time-domain (FDTD) model

1. A linear 3-D FDTD model has been developed to model wave propagation in soil and the interactions of elastic waves with buried objects. Stratification of the soil and the structure of the target are accounted for in the FDTD code. The model is presented in publications P1, P2, P3, and P4.

2. The linear 3-D FDTD model has been validated by comparison with measurements made at the experimental facility at Georgia Tech [P1, P2, P3, and P4].

3. The linear 3-D FDTD model has been used to study the interactions with a set of buried mines and clutter objects. [P1, P3, and P4].

4. The effects of trenching have been modeled numerically [P2]. The numerical trenching model has been validated experimentally.

5. Initial investigations have been performed on techniques for including the non-linearity and the loss of the sand in the model.

6. Because of the computational requirements for the model, a Beowulf cluster consisting of fifty 500 MHz Pentium III processors and 6 GB of memory has been assembled as part of this project. The 3-D FDTD model has been implemented to run efficiently on this Beowulf cluster.

Soil Property Measurements

1. Physical properties of wet compacted sand and local soil samples have been measured through seismic propagation experiments involving surface coupled accelerometers.
2. The depth dependence of shear wave velocity in the experimental model has been studied using an inversion technique involving surface measurements and the three dimensional model [P1]. The

technique presumes the depth dependence of the velocity to be the dominant source of surface wave dispersion. The vertical profile is then derived by matching measured time domain waveforms to model predictions.

3. Experiments have been performed to investigate the non-linear properties of the sand in the experimental model as a function of frequency and range [P5]. These experiments have shown that the transfer function of the measurement system has strong non-linearities above 1 KHz in the range of normal drive levels. Increasing the source drive signal by a factor of 10 produces significant non-linearity over the entire operating bandwidth (100 Hz - 2 KHz). The dominant source of the measured non-linearities was found to be source to surface coupling and near source effects. Evidence of non-linear dispersion in the propagation path was also observed.

Collaboration with NPS

1. In December 1999, a three-man team from Georgia Tech toured facilities at NPS and met with Tom Muir to discuss plans for field tests.

2. A series of pilot field tests was performed form July 16 to August 16, 2000 to test the propagation characteristics and ambient noise field at the NPS test site. These tests were intended to resolve logistical issues which will be encountered in full system tests.

RESULTS

In previous experimental work, resonances were observed directly above buried land mines. By using the FDTD model, Georgia Tech has shown that the resonances are due to flexural waves in the layer of soil above the mine and in the case of the mine. These resonances significantly enhance the response of mines making them easier to detect than other similarly sized non-resonate clutter objects. The resonances are a distinctive feature of the buried mines that can be used to distinguish them from common types of buried clutter. As an example, the particle displacement of the surface of the earth is shown in **Figure 1** for four instances in time. In these graphs, the color indicates the relative size of the magnitude of the surface displacement. The color scale goes from white to red to blue to black, where white indicates the smallest displacements and black indicates the largest displacements. In this simulation, three mines, four rocks, and one stick were buried. The locations of the mines are clearly visible in these graphs while the effects of the rocks and stick are much less apparent even in the graphs with an additional 30 dB of dynamic range. These results are presented in more detail in papers P1, P2, P3, and P4.

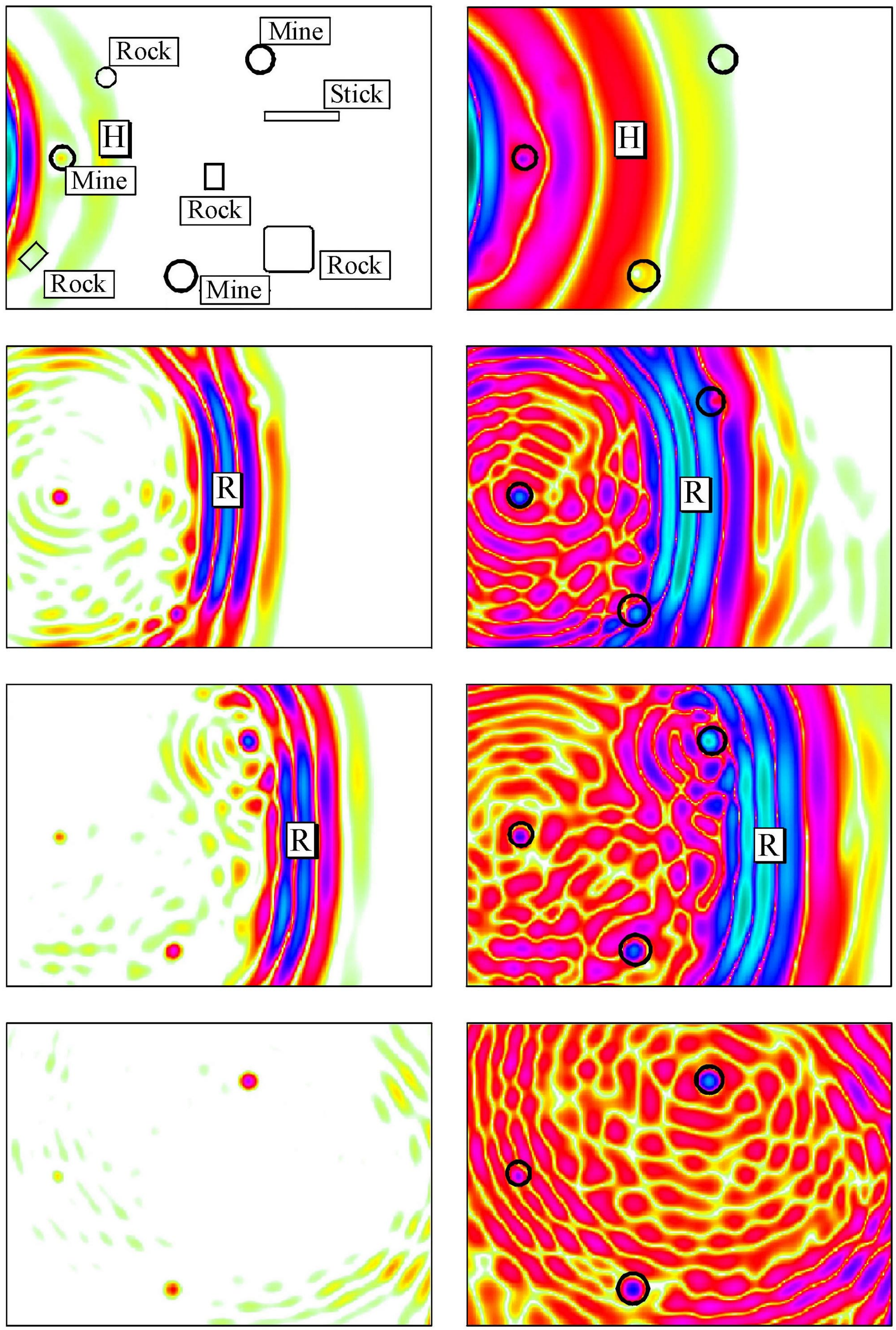

Figure 1: Three mines, 4 rocks and a wooden stick buried in the ground; pseudo color plots of the normal particle displacement on the surface with a dynamic range of 40dB (left column) and (b) 70 dB (right column).

IMPACT/APPLICATIONS

The development of an operational mine detection system with a higher probability of detection and a lower false alarm rate than those currently available. All of the techniques and models developed for this project may be useful for other shallow seismic applications. These include the location of unexploded ordinances, buried pipes, non-destructive testing, and archaeology.

TRANSITIONS

NPS is currently using the 2-D version of the FDTD model to simulate their seismic mine detection concept. In their work, they use polarization filters of back-scattered seismic waves. Georgia Tech is currently working on a three-dimensional model for their experimental system.

RELATED PROJECTS

1. Army Research Office (ARO) contract number DAAH04-96-1-0448 ("Investigation of an Acousto-Electromagnetic Sensor for Detecting Land Mines") is a grant to Georgia Tech through the Multi-University Research Initiative (MURI) entitled “Multidisciplinary Research for Demining.” The ARO MURI project is an experimental and numerical investigation of a seismic mine detection system. The project described in this report extends the numerical models developed as part of the ARO MURI project.

2. Ongoing mine detection research at the Naval Postgraduate School (NPS) headed by Dr. Tom Muir is closely related to work at Georgia Tech. The NPS makes use of the Georgia Tech numerical models, and Georgia Tech makes use of the NPS field measurement site, facilities, and expertise.

PUBLICATIONS

P1: Schroeder, C.T. and Scott, W.R., Jr., “Three-Dimensional Finite-Difference Time-Domain Model for Interaction of Elastic Waves with Buried Land Mines,” Proceedings of the SPIE: 2000 Annual International Symposium on Aerospace/Defense Sensing, Simulation, and Controls, Orlando, FL, Vol. 4038, April 2000.

P2: Scott, W.R., Jr., Schroeder, C.T., Martin, J.S., and Larson, G.D., “Investigation of a Technique that Uses Both Elastic and Electromagnetic Waves to Detect Buried Land Mines,” Proceedings of the AP2000 Millennium Conference an Antennas and Propagation, Davos, Switzerland, April 2000.

P3: Schroeder, C.T., Kim, K., and Scott, W.R., Jr., “A Three-Dimensional Model for Elastic Waves in the Ground,” Proceedings of the 139th Meeting of the Acoustical Society of America, Atlanta, Georgia, June 2000.

P4: Schroeder, C., and Scott, W.R., Jr., “Three-Dimensional FDTD model to Study the Elastic Wave Interaction with Buried Land Mines,” Proceedings of the 2000 International Geoscience and Remote Sensing Symposium, Honolulu, Hawaii, July 2000.

P5: Albert, B.C., “Characterization of Nonlinearities in the Propagation of High Frequency Seismic Waves,” Thesis, School of Mechanical Engineering, Georgia Institute of Technology, April 2000.